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RECENT BRENVA ROCK AVALANCHES (VALLEY OF AOSTA): NEW CHAPTER IN AN OLD STORY?

ABSTRACT: DELINE P., *Recent Brenva rock avalanches (Valley of Aosta): new chapter in an old story?* (IT ISSN 0391-9838, 2001).

Two rock avalanches have affected the Brenva Glacier (Mont Blanc Massif, Italy) in the 20[th] Century, in 1920 and 1997. The low-friction substrate offered by the glacier caused excessive run-out distances, and both avalanches reached the valley floor. In both cases, vertical and horizontal travel distances exceeding respectively 2 and 5 km were attained. The 1920 deposit on the glacier caused an advance untill 1940, the only one of this kind in the Alps.

These rock avalanches, each triggered by 2-3 x $10^6 m^3$ rockfall, occured during opposite phases of the glacial cycle (advance in 1920, retreat in 1997), but a large part of the mobilized rock and ice mass was spread on the distal side of the right-lateral moraine in both events. Historical and mainly geomorphological evidences suggest that several rock avalanches have occured during the Holocene. The most recent, except those of this century, might have taken place in the 14[th] Century. These rockfalls might be in relation with the modification of rockwall permafrost due to the global warming (+ 0.50 °C during the 20[th] Century, + 1.25 °C in the Alps), although the understanding of this possible link remains insufficient.

KEY WORDS: Rock avalanche, Climate variations, Holocene, Little Ice Age, Mont Blanc Massif, Brenva Glacier.

RIASSUNTO: DELINE P., *Frane di crollo recenti sul Ghiacciaio della Brenva (Valle d'Aosta): un nuovo capitolo di una vecchia storia?* (IT ISSN 0391-9838, 2001).

Due frane di crollo sono cadute sul Ghiacciaio della Brenva (Gruppo del Monte Bianco) nel XX secolo, rispettivamente nel 1920 e nel 1997. La presenza del ghiacciaio, riducendo l'attrito, permise a queste frane di raggiungere il fondo della Val Veny: la distanza percorsa fu di 2 km in verticale e di oltre 5 km in orizzontale. Il deposito abbandonato dalla frana del 1920 sul ghiacciaio causò un'avanzata della fronte fino al 1940, caso unico nelle Alpi in tale periodo.

I due fenomeni presero avvio dal crollo di diedri rocciosi del volume di 2-3 x $10^6 m^3$ dalle pareti che contornano il ghiacciaio. I due eventi ebbero luogo durante fasi glaciali differenti (avanzata nel 1920, ritiro nel 1997). Una gran parte della massa mobilizzata (roccia e ghiaccio) si depose in entrambe le occasioni sul fianco esterno della morena laterale destra. Indizi storici e soprattutto geomorfologici suggeriscono una successione di frane analoghe durante l'Olocene. La più recente, a parte quelle citate, potrebbe essersi verificata nel Trecento. Queste frane di crollo potrebbero essere in relazione con le modificazioni del permafrost indotte nelle pareti rocciose dal riscaldamento globale (+ 0.50 °C nel XX secolo, + 1.25 °C nelle Alpi), benché la comprensione di questa possibile relazione sia ancora decisamente insufficiente.

TERMINI CHIAVE: Frana di crollo, Variazioni climatiche, Olocene, Piccola Età Glaciale, Gruppo del Monte Bianco, Ghiacciaio della Brenva.

RESUME: DELINE P., *Ecroulements catastrophiques récents sur le glacier de la Brenva (Vallée d'Aoste) : le nouveau chapitre d'une longue histoire?* (IT ISSN 0391-9838, 2001).

Deux écroulements catastrophiques se sont produits sur le glacier de la Brenva (massif du Mont Blanc, Italie) au XX[ième] siècle, en 1920 et 1997. Le coefficient de frottement réduit par la présence du glacier explique les grandes distances parcourues (2 km verticalement, 5 km horizontalement), les écroulements atteignant le fond de la vallée. Le dépôt supraglaciaire de 1920 entraîna une avancée du front jusqu'en 1940, exceptionnelle dans les Alpes durant cette période.

Ces écroulements ont été engendrés par l'effondrement de parois rocheuses, avec des niches d'arrachement de 2-3 x $10^6 m^3$. Ils ont eu lieu pendant deux phases glaciaires différentes (avancée en 1920, retrait en 1997). Une grande partie de la masse mise en mouvement (roche et glace) fut déposée dans les deux cas sur le flanc externe de la moraine latérale droite. Des éléments historiques et surtout géomorphologiques indiquent une succession d'écroulements du même type pendant l'Holocène. Le plus récent , mis à part ceux du XX[ième] siècle, pourrait avoir eu lieu au XIV[ième] siècle. Ces écroulements rocheux pourraient être liés aux modifications du pergélisol dans les parois rocheuses de haute altitude, entraînées par le réchauffement global (+ 0.50 °C pendant le XX[ième] siècle, + 1.25 °C dans les Alpes), bien que la compréhension d'une telle relation reste encore très insuffisante.

MOT CLES: Écroulement catastrophique, Changements climatiques, Holocène, Petit Age Glaciaire, Massif du Mont Blanc, Glacier de la Brenva.

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INTRODUCTION

High mountain rockfalls are generally considered to have followed Lateglacial glacier retreat (Evans & Clague, 1994). But as post-Little Ice Age warming climate is supposed to lead to permafrost degradation, a higher frequency of rockfalls might be one of the consequences (Haeberli & *alii*, 1997).

On 18 January 1997, for the second time during the 20^{th} Century, the Brenva Glacier experienced the impact of a large rock avalanche. This glacier is one of the largest on the Italian side of the Mont Blanc Massif (fig. 1) A huge avalanche hurtled down the 2 000 m high mountainside in less than three minutes. The air blast destroyed 200 years old trees on the bottom of opposite valley side (1 500-1 600 m of elevation) and even affected the lower skilift on the foot of the Mont Chétif (2 000 m). Here, skiers were dropped into semi-darkness while tree branches were pulled up and thrown by the violent wind. On the tunnel platform, car windscreens were pitted with rocky dust contained in the snow cloud, and one km downstream at Entrèves cableway station, parked cars were covered with 5 cm of packed ice powder.

Then, a dust cloud was blown over Courmayeur and on down the valley. Two skiers were killed and about ten slightly injured on the road from Val Veny, along the Doire stream bed.

A TWO MILLION m^3 ROCKFALL

During 1996 Summer, rockfall deposits of some 10^4 m^3 were observed by guides in the Col Moore area, where a big rockfall (1×10^5 m^3) succeeded on 16 January 1997. Two days later, the huge drift avalanche was triggered by the partial collapse of the Gendarme Rouge, a 450 m high granitic spur towering above the Brenva Glacier at an elevation of 3 872 m. This 2×10^6 m^3 rockfall created a 250 m wide, 300 m high and some tens of metres deep scar (fig. 2). The mass movement comprised a large volume of ice

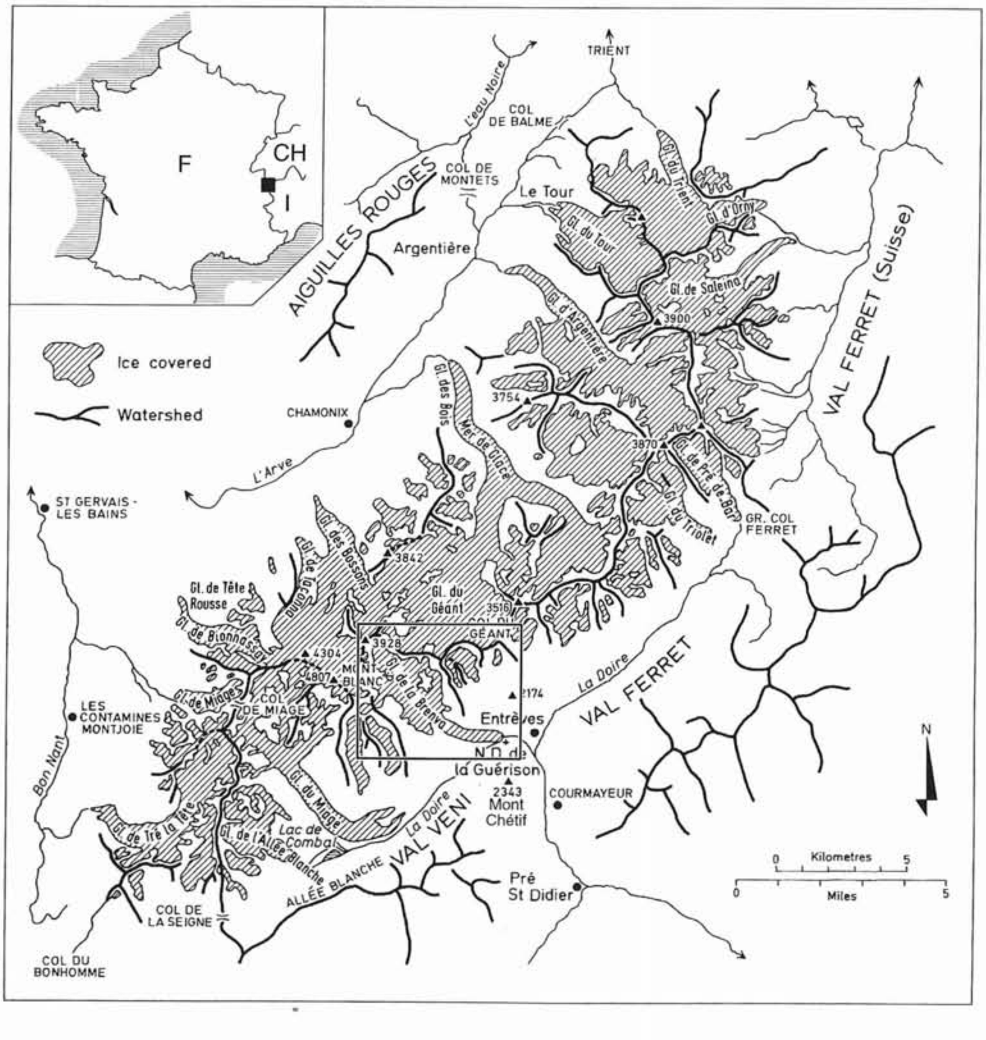


FIG. 1 - Location map (after Grove, 1988, modified).

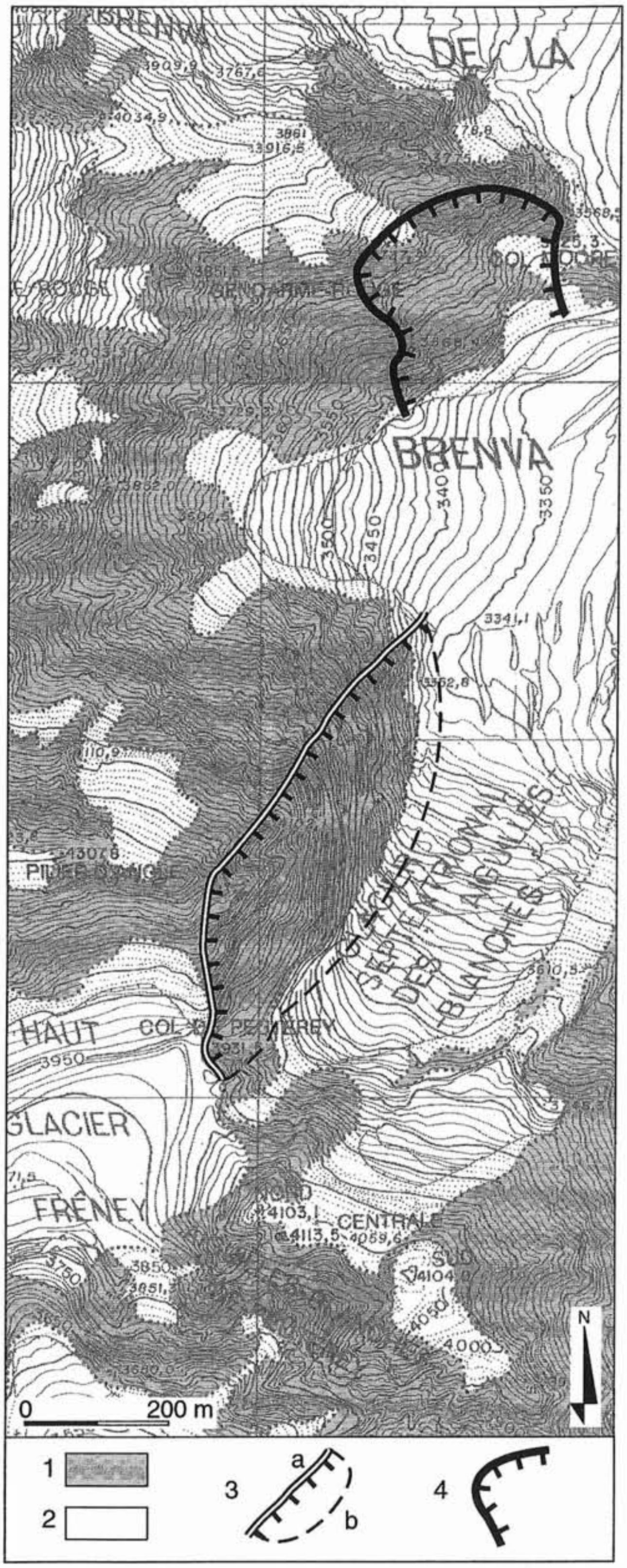


FIG. 2 - 1920 and 1997 scar map (1:10 000). 1. Rockwalls; 2. Glaciers and firns; 3. a. 1920 rockavalanche scar, b. bottom limit of collapsed rockwall; 4. 1997 rockavalanche scar. [Topographical map: *Archivi topo-cartografici della Regione Autonoma Valle d'Aosta - autorizzazione n. 52 (18.08.1999)*].

and firn, excavating a wide trough down the glacier and forming a snow aerosol. Horizontal and vertical displacements were respectively 5 500 m and 2 150 m. No seismic event triggered the rockfall, but its shock was recorded by the Grenoble and Emosson (Valais) seismographs.

The foot of the NE face of Mont Noir de Peuterey was planed down, superficial debris being completely removed so that bedrock became visible. On reaching the lower part of the glacier, the rock avalanche spread in two directions (fig. 3):

i) one lobe overflowed the right-lateral moraine, razing trees on the distal face, and reached the Doire River.

ii) the other part was channelled by the right lateral moraine and reached the glacier front, just below the Notre-Dame-de-Guérison cliff. The Plan-Ponquet hotel, closed in winter, was just spared, and a little lake was dammed by the deposit in the Doire stream bed. The lake level rose of 1-1.5 m in 4-5 days, until the river began to flow under the deposit.

The rockavalanche deposit was formed by 2 x 10^6 m^3 of granite rock and about 2 x 10^6 m^3 of ice, firn and snow. Mean thickness after melting is about 1 m on the lower (debris-covered) part of the glacier and about 2 m near the Doire stream bed. There, rock varnish, mosses and sometimes little lichens (*Rhizocarpon geographicum*) cover one or more sides of most big boulders present. This indicates that these boulders were deposited prior the 1997 and that older deposits are a debris source for later rockavalanches. The deposit surface was characterized by angular boulders without weathering (but glacially-rounded boulders coming from the lateral moraine are common), by a «tousled» facies, *i.e.* with debris deposited on top of boulders by ice melting, and by abundant gravel and sand matrix due to comminution. A cross section of the deposit was made on the sand quarry access road during the 1997 summer clearing-up operations. Six months after the event, it showed a 10 m thick deposit, with decimetric ice blocks and decimetric to metric granite boulders, coated with a packed brownish powder of ice and granite. Beneath the deposit, a 0.50 m packed snow layer resulted from the 18^{th} January snow cover.

A STURZSTROM ON A GLACIER

This rockavalanche exemplifies a sturzstrom, defined by Hsü (1975) as «a stream of very rapidly moving debris derived from the disintegration of a fallen rock mass of very large size; the speed of a sturzstrom often exceeds 100 $km.hr^{-1}$, and its volume is commonly greater than 1 x 10^6 m^3». As a grain flow, the sturzstrom motion results from «a reduction of frictional resistance of colliding blocks dispersed in a dust suspension» (*Ibid.*). The interstitial fluid might be watery mud, compressed air or above all small particles between boulders forming a dense dust cloud with buoyancy force. This rocky dust explains the brown color of the airborne cloud in the valley, and is found in the deposit matrix.

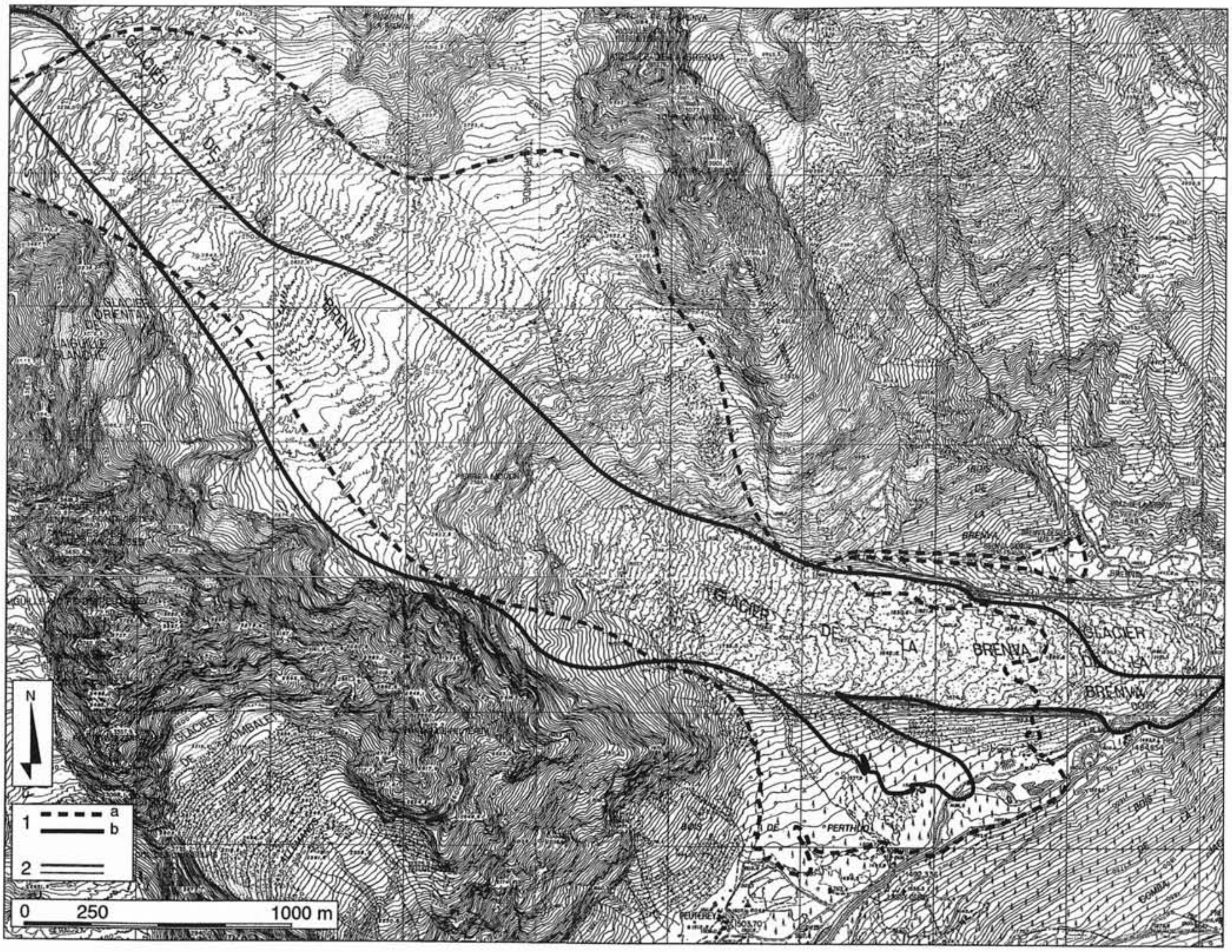


FIG. 3 - 20th Century Brenva rockavalanche map. 1. a. 1920 rockavalanche limits (after Orombelli & Porter, 1982, modified), b. 1997 rockavalanche limits; 2. Moraine crests. [Topographical map: *Archivi topocartografici della Regione Autonoma Valle d'Aosta - autorizzazione n. 52 (18.08.1999)*].

The excessive travel distance (L_e), «defined as the horizontal displacement (L) of the tip of the sturzstrom beyond the distance one expects from a frictional slide down an incline with a normal coefficient of friction of tan 32° (0.62), namely,

$$L_e = L - H/\tan 32$$

where L is the horizontal displacement (5 500 m) and H is the vertical displacement (2 150 m)».

For the 1997 Brenva sturzstrom, L_e = 2 032 m. This excessive travel distance is closed to that of the Madeleine rockavalanche (Haute Maurienne), but of which the volume was about 100 x 10^6 m^3 (Couture & *alii*, 1997). In the case of the Brenva rock avalanche, the smaller volume was compensated by the low-friction glacier substrate. In effect, rockavalanche mobility on glacier is enhanced by four factors (Evans & Clague, 1988):

- lower kinetic friction coefficient of a debris/snow or debris/ice interface ($0.18<\mu<0.42$)
- frictional resistance reduced by the generation of water or steam pressures at the base of the moving debris
- fluidisation of the debris by incorporation of ice and snow
- channelling and air-launch effect of the debris by lateral and end moraines.

«As a first approximation, interaction with glacier ice significantly enhances rock avalanche mobility», at an average of 24% (*Ibid.*). This is confirmed with two recent rock avalanches on glacier (tab. 1).

TABLE 1 - Characteristics of three recent sturzstroms due to comparable rockfalls

Sturz strom	Year	Volume (10^6 m^3) total	rock	Travel distance (m) vertical	horizontal	excessive	References
North Creck (Can)	1986	?	1-2	745	2.850	1.648	Evans & Clague, 1988
Mount Cook (Nz)	1991	14	2,5	2.700	6.900	2.545	Kirkbride & Sugden, 1992; Ancey (Ed.), 1996
Brenva (I)	1997	4	2	2.150	5.500	2.032	This paper

THE NOVEMBER 1920 ROCK AVALANCHES

The rockwalls in the upper basin of the Brenva Glacier are orange-coloured, due to rock varnish, but some are grey, indicating recent rockfall scars as on the Gendarme Rouge spur. The last big rock avalanche occured in November 1920.

The event took place in two stages:

1) On the afternoon of 14 November, at about 14.30, «un premier décollement de roches eut lieu à la base de la paroi [Grand Pilier d'Angle] et latéralement au couloir de Pétéret» (Brocherel, 1920) (fig. 2). Two vertical white grooves were dug in the rockfall scar by the rock friction (Valbusa, 1921). The rock mass planed down the glacier surface, triggering an avalanche described by witnesses as a dense cloud «simile a un fiocco di lana che si movesse». Boulders were launched into the air when it reached the part of the rock step not covered by the icefall, named Pierre à Moulin.

At its bottom, the avalanche was divided by the ice cone formed by the regular fall of seracs (fig. 3):

i) the main part overflowed the right-lateral moraine, destroying the trees on a width of about a hundred m at the foot of the SE face of Mont Noir de Peuterey above an elevation of 1 500 m The deposit front was digitate, and formed predominantly from ice blocks, reaching some m high;

ii) the second part overflowed the left-lateral moraine and formed a *c.*1 km long ice block deposit (0.4 x 10^6 m^3) between the moraine and the valley side (*Ibid.*).

After the event, a thick fog hid the glacial basin: «Les jours suivants, de légers flocons de poussière flottaient par instant au ras de la montagne, dénonçant des chutes de pierres» (Brocherel, 1920).

2) On the afternoon of November 19, four rock avalanches occured between 14.00 and 16.45. A dense cloud was generated by the first one, hindering observations; the last one was by far the largest. According to Brocherel, each rock avalanche spread successively down the distal side of the right-lateral moraine; according to Valbusa the earlier deposits on the lower part of the glacier were reworked by the last rock avalanche, which spread on the main part of the moraine flank. In each case, the rock avalanche path was different from that of November 14: on November 19, the avalanche extended over the whole width of the glacier upstream of the Pierre à Moulin. It ran 50m up the base of the west slope of the Rochers de la Brenva, veneering a granite and ice roughcast on the rockwall before overflowing the right-lateral moraine (fig. 3).

In contrast to 1997, the 1920 rock avalanches did not generate an air blast: trees on the opposite valley side or on the Perthud plain were not destroyed. A dense ice and granite dust slowly settled in the Brenva high basin, in the Tour Ronde basin (for about 1 km along the deposit left margin), on the Rochers de la Brenva (a 2-3 mm layer) and on the opposite valley side above 1 800 m, in the Col Chécrouit area (Valbusa, 1921). The lack of an air blast suggests that the five 1920 rockavalanches were not of the sturzstrom type but rather of the wet snow avalanche type, «un mortier mou qui s'est écoulé en nappes successives sur la pente du glacier» (Brocherel, 1920). However, the 50 m high run-up on the Rochers de la Brenva might be a sturzstrom indicator.

THE 1920 SCAR AND DEPOSIT

The 1920 rockfall scar is visible on the Grand Pilier d'Angle because of its grey color, which contrasts sharply with the light brown rockwall varnish. Brocherel made a rough calculation of its dimensions : 800 m high, 150 m wide, and 50 m deep, « soit, en chiffre rond, à peu près trois millions de mètres cubes », although these dimensions give a 6 x 10^6 m^3 volume.

By cross-referencing Brocherel's descriptions (1920) with cartographic data, the scar can be reconstructed and measured more precisely (fig. 2). Its surface is about 0.24 x 10^6 m^3 and its mean thickness might be of the order of 12 m considering i) the absence of a hollow scar ii) the five rockfall stages iii) the upslope growth of the scar by retrogressive roof-collapse during the event: «les décrochements des blocs ont procédé du bas de la paroi au faîte de l'épaulement, par soustraction progressive des points d'appui, chaque départ de roche provoquant la chute de la partie immédiatement supérieure» (*Ibid.*).The rockfall volume might be of about 3 x 10^6 m^3. Col de Peuterey was lowered: its elevation passed from 3 987 m to 3 934 m (Orombelli & Porter, 1981), that is to say more than Valbusa thought (*c.* 30 m).

The deposit was formed by an ice and granite block mixture, without topographic order, in which contemporary photographs show ice to form the greater part of the mass. The deposit thickness varied from a few cm in the higher part of the right-lateral moraine to about 50 m in the Doire stream bed at its SE limit, with a maximal thickness of 10 m on the lower part of the glacier and in the Perthud plain (Brocherel, 1920; Valbusa, 1921).

The volume was estimated by Valbusa to be 4-5 x 10^6 m^3 on the lower glacier, 2 x 10^6 m^3 in the south of the right-lateral moraine, and 0.4 x 10^6 m^3 in the north of the left-lateral moraine, that is to say about 6.5-7.5 x 10^6 m^3 all in all, «ghiaccio naturalmente per la grandissima parte». After melting, deposit mean thickness scarcely exceeded 1 m, to give an estimated rock volume of about 2 x 10^6 m^3. As Valbusa did not take into account either the deposit on the upper glacier nor the dust, the 1920 and 1997 rock avalanches may be considered as events of equivalent volumes of 2-3 x 10^6 m^3, creating similar deposits.

In contrast to 1997, the 1920 rock avalanche did not reach the glacier front because i) its path was controlled by the Rochers de la Brenva spur, which deflected the flow so that it overflowed subperpendicularly the right-lateral moraine ii) the glacier surface was at the same level or even higher than the lateral moraine crests because of a glacier advance phase, so the moraines presented no obstacle; in 1997, the glacier retreat converted the right-lateral moraine into a dyke which partially channelled the flow.

BRENVA ROCK AVALANCHES DURING THE HOLOCENE

Are the two 20[th] Century rock avalanches isolated events? Examination of the right-lateral moraine of the Brenva Glacier indicates that the moraine was not built only by glacial processes, contrary to the nearby Miage Glacier.

While both glaciers have right-lateral moraines of similar height (>200 m, but partially covered for the Miage) and a 40° mean slope angle, the Brenva moraine presents a basal overthickness of between 65 m and 90 m compared to only 25 m for the Miage moraine (fig. 4). This basal overthickness is formed by deposits due to gravity accumulation, melting water and glacial outbursts which generate breaches in the lateral moraine crests. These outbursts are particularly frequent on the Brenva Glacier. The main breach of the Brenva moraines formed in 1928 (Orombelli & Porter, 1982) and operated again during the last glacial advance which reached a peak in 1986, while 8 new smaller breaches appeared in this period. Below the 1928 breach, the distal side of the moraine displays debris flow deposits covering an area 100-200 m wide, with signs of recent activity (fig. 5). But the greater overthickness of the Brenva moraines results above all from successive rock avalanches of the 1920/1997 type, which have spread the right-lateral moraine to the south : for a 150 m high section of each moraine, the horizontal distance between foot and crest of the moraine is 450 m for the Brenva and 230 m for the Miage (fig. 4). Considering that any one rock avalanche deposit is only a few metres thick after ice melting, and that part of the deposit consists of boulders remobilized from older deposits, the Brenva basal overthickness could indicate a rather high frequency of rock avalanches on this glacier during the Holocene.

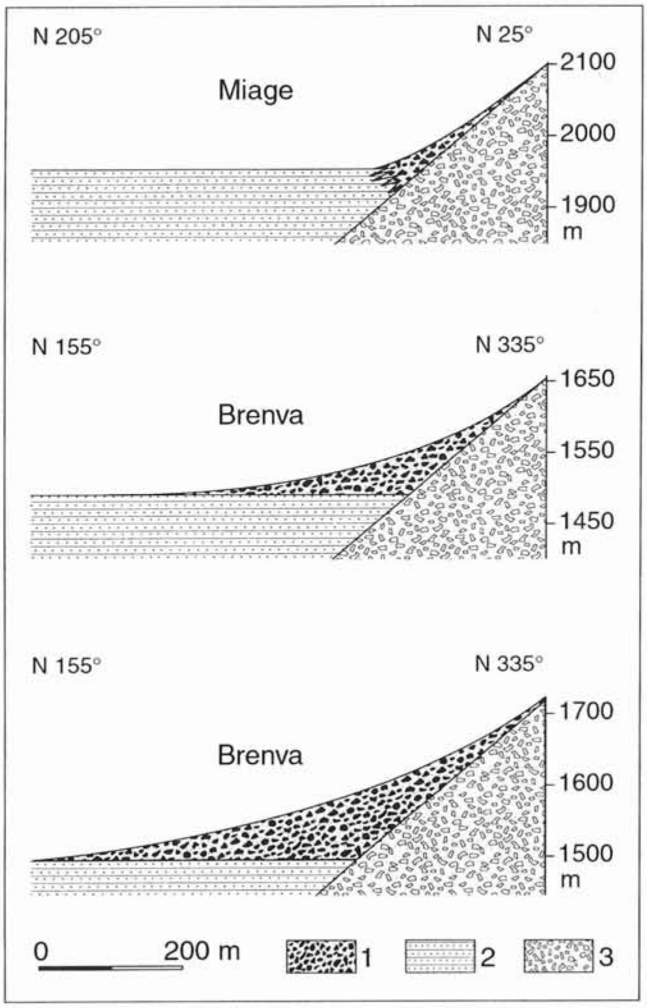
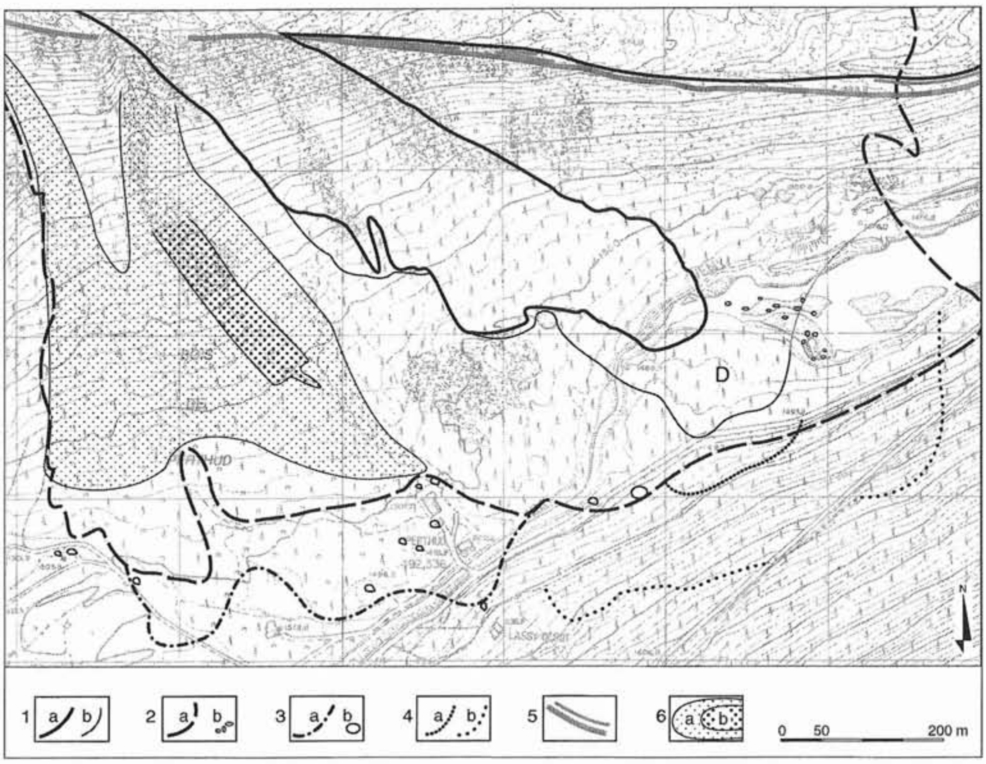


FIG. 4 - Brenva and Miage Glacier right-lateral moraine cross sections. 1. Basal overthickness deposit; 2. Fluvioglacial deposit; 3. Lateral moraine.

NE of Perthud, granitic boulders lie between the road and the Doire River. About 25 m thick in relation to Plan-Ponquet lake, this deposit (fig. 5: D) has constrained the river away from the Mont Chétif slope. Located in the basal overthickness continuation, it received a thin debris layer in 1997. The 1920 deposit was a boulder layer a few m thick in this area; this thickness is inferred from the nearby deposit front, immediately south of the road, along which four *Picea* were spared, while eyewitness accounts report a 10 m long boulder was toppled through 90° (though this is not supported by field observation). The 25 m thickness of this Doire right bank deposit indicates that successive rock avalanches have occured throughout the Holocene.

FIG. 5 - Brenva rockavalanche holocene deposit map. 1-4. Rockavalanche limits (in grey: supposed): 1. 1997, a. continuous blocky deposit, b. thin and discontinuous deposit; 2. 1920, a. limits, b. boulders in stream bed; 3. 14th C. (?), a. limits, b. big boulders; 4. Ante Little Ice Age, a. older, b. oldest; D. 25 m thick deposit; 5. Moraine crests; 6. Debris flow deposit, a. post 1928, b. post 1960's. [Topographical map: *Archivi topocartografici della Regione Autonoma Valle d'Aosta - autorizzazione n. 52 (18.08.1999)*].



The base of the opposite valley side of Val Veny displays granitic boulder accumulations of various densities. Upslope, the boulder density is smaller in the area between Lassy-Dèsot and the beginning of the Pré Pascal access road, in the continuation of the lateral moraine basal overthickness. Because it is absent to the SW of Lassy-Dèsot, this deposit is presumed not to be lateglacial till of the Val Veny Glacier, of which characteristic elements (well-rounded or flat iron-shaped quartzite, gneiss, black crystalline schists), are present above 1 515-1 520 m. The absence of moraines or any other glacial form indicates that neither is this deposit a till from the lateglacial Brenva Glacier extending across the valley. Rather, it is interpreted as a rock avalanche deposit which may have crossed the former Val Veny Glacier.

Lastly, the height of the Brenva lateral moraine, similar to the Miage, indicates that a debris-cover is the characteristic state of the glacier, with rock avalanches the dominant debris source. A fossil tree stump with a radiocarbon age of 1 170 +/– 55 yr BP (718-998 cal. AD) was located 8 m below the crest of the right-lateral moraine (Orombelli & Porter, 1982), suggesting that moraine building (and consequently rock avalanche activity) has probably taken place throughout the entire Holocene period.

A 14th CENTURY ROCK AVALANCHE?

The legend about Saint-Jean-de-Perthud might be a historical sign of Holocene rock avalanche activity. This village is supposed to have been located N or NW of the present hamlet named Perthud (fig. 5). As mentionned by Orombelli & Porter (1982), «local tradition states that the community was destroyed and overrun by the glacier as a punishment to its inhabitants for cutting hay on Santa Margherita's Day». Its location in the position of the present right moraine during the late Middle Ages (Virgilio, 1883) would concord with this hypothesis, but the radiocarbon-dated wood disproves this assertion : the moraine is very much older than the Middle Ages. According to Vivian (1975), Dollfus-Ausset stated that a 1300 AD manuscript located the village in front of Notre-Dame-de-Guérison, which would mean that the glacier front was at that time (and for several preceding centuries) far back from its Little Ice Age maximum. As the village, may be founded in the 8th Century (Duc, 1915) and considered to be the oldest parish in this area, is no longer mentioned in the late Middle Ages according to Le Roy Ladurie (1967), its destruction might have taken place in the 14th century.

To be so sudden, this destruction might not be due directly to the glacier, whose advances are slow, but to a rockavalanche over the glacier, similar to the 1920 and 1997 events. According to Dollfus-Ausset, Saint-Jean-de-Perthud was «englouti par un éboulement de la montagne et ensuite envahi par le glacier de la Brenva» (Vivian, 1975). The deposit of ice and rock boulders would have given rise to the legend, unless the glacier had experienced a large advance due to the debris cover protecting the ice against solar ablation : between 1920 and 1940, the Brenva front advanced nearly as far as its 1818-1820 maximum, while others glaciers of the Mont Blanc Massif were retreating. If the village was located in the present frontal area, testimonies about house wood brought down by the glacier (Virgilio, 1883) would win some credibility. Lastly, the right-lateral moraine overflowed by the glacier, as drawn by Jallabert in 1767 (Saussure, 1786), could not destroy the village because it was assuredly not built on the steep part of the moraine distal side.

A part of the deposit of this destructive rock avalanche early in the 14^{th} century might appear W of Perthud, beyond the 1920 deposit, where boulders are colonized by >200 yr stumps, while a lichenometric study (Giambastiani, 1983) gives an age of about 260 yr to a (non located) Brenva deposit.

STRUCTURAL CONTROL ON ROCK AVALANCHES

The rock avalanches occur on rockwalls which are marked by a dense network of fractures, mainly positioned towards N to N 20° (Variscan structure) and N 45° (alpine structure). In the Mont Blanc Massif, zones of alpine mylonitization of this latter orientation are commonly associated with cols (*e.g.* cols Rey, Eccles or Peuterey); in effect, mylonito-schists are rocks of low strength and have been eroded preferentially. Most of these rockwalls present an marked break-of-slope and a subvertical cliff, which allow gravitational collapse. In the high Brenva Glacier basin, large areas of grey rockwalls are visible, indicating the rockfall activity within at least the last century. But apart from this style of structural control, the effects of changing climatic conditions on rock avalanche occurrence deserves investigation.

ROCK AVALANCHES AND CLIMATE VARIATIONS

Glacier retreat during Lateglacial time was expressed by a thickness decrease, estimated to be 200 m in the upper Brenva Glacier based on the topographic reconstruction of the upper Val d'Aosta Glacier during the maximum Würm advance (Orombelli & Porter 1981). This decrease could have led to the destabilization of the bases of rock walls, due to rock relaxation when ice pressure stopped. The debris supply to the glacier was probably very active, and lateral moraine cores would have been built rapidly. During the Holocene, rockwall equilibrium was more or less set up, but rock collapses might still occur due to climatic variations.

High Brenva basin rockwalls are located in the permafrost altitudinal belt, where ice in superficial cracks is comparable to a cement. Recent observations indicate permafrost modification: lower limit in the Alps would have risen of about 150-250 m since 1850 (PNR 31, 1998). Temperatures anomalies during the 20^{th} Century are now well established, with a fivefold amplification of the global climate interannual variability in the Alps (Haeberli & Beniston, 1998). 1920 and 1997 rockavalanches concord with two intense warming periods, but the warmest period, in the 1940s, did not trigger a rockfall. Minimum temperatures have risen at a rate three times faster than the maxima since the 1950s with respective anomalies of 0.84° and 0.28°C, while during the mild winters of the 1979-1994 period, the higher the elevation, the stronger the positive anomaly, with 3°C above an elevation of 2 500 m (*Ibid.*). With the 1980s warming, alpine permafrost temperature is rising at relatively high rate: 0.4°C between 1987 and 1995 at 20 m deep in the Murtèl-Corvatsch rock-glacier, Grisons (*Ibid.*). In the Mont Blanc Massif, water often flows in gullies during summer, while small rockfalls occur in climbing routes: the frequent snowfalls during this season are rapidly converted into water, which penetrates deeply into the cracks, generating very high hydrostatic pressures (Bozonnet, 1994). For example, the Drus rockfall (09/1997, 13 500 m^3) partially destroyed the Directissime Américaine and the Thomas Gross routes. During the same 1997 summer, successive rockfalls happened on the Aiguille Noire de Peuterey SE face, above 3 000 m elevation, producing a dense brown cloud which remained for several days in the Fauteuil des Allemands cirque. Changes in the observation conditions might explain a higher frequency of these phenomenons, but ice melting could be suspected: ice-cemented blocks from 0.5 to 2 m^3 in volume were present in the deposit of the Val Pola rockavalanche (07/1988, Valtellina); this «suggests that permafrost-related processes, such as ground ice melt due to climatic warming and connected changes in groundwater regimes could have played a role in activating the landslide» (Dramis & *alii*, 1995). The 1997 Brenva scar bottom shows flowing water, in spite of its elevation: being a South-facing spur, the Gendarme Rouge is rapidly cleared of its snow in summer.

CONCLUSION

There are difficulties in explaining the Brenva rock avalanches by climate variations because i) no indirect dating of Holocene activity has been found, due to the deposit characteristics ii) the three last events (14^{th} c., 1920, 1997) occured in warmer periods, but the first rock avalanche remains hypothetical while the 20^{th} century events occured at the beginning and at the end of the present post-Little Ice Age warming interstage. However, these two events within 77 years could indicate increasing activity in the area, while the possible existence of a village suggests that the Middle Ages were rather morphodynamically stable, as there seems was the main part of the Little Ice Age too: Perthud forest was an old forest, described as a *Picea* or *Abies* forest prior to 1920.

The geometry of the Brenva Glacier basin, with the SE orientation of the lower glacier, explains why the main rock avalanches cross the glacier, and the basal overthickness of debris which has formed distal to the right-lateral moraine shows that rock avalanche activity has lasted all the Holocene.

Because of fatalities in 1997, a legal action was taken against those in charge of the Regione Autonoma della Valle d'Aosta, the town of Courmayeur and the ski resort. The basis of the legal case is the matter of the predictibility of the 1997 event. Relying on geomorphological evidence, it has been demonstrated that this event is the latest in a long series. But prediction requires anticipation of the exact timing and form of the next rock avalanche. The rockwall movement is now measured with a telemeter, directed by the Geotest firm, which should permit rockfall prediction on the Gendarme Rouge spur.

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